

Baryogenesis and neutron-antineutron oscillation at TeV

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We propose a TeV extension of the standard model to generate the cosmological baryon asymmetry with an observable neutron-antineutron oscillation. The new fields include a singlet fermion, an isotriplet and two isosinglet diquark scalars. There will be no proton decay although the Majorana mass of the singlet fermion as well as the trilinear couplings between one isosinglet diquark and two isotriplet diquarks softly break the baryon number of two units. The isosinglet diquarks couple to two right-handed down-type quarks or to a right-handed up-type quark and a singlet fermion, whereas the isotriplet diquark couples to two left-handed quarks. The isosinglet diquarks mediate the three-body decays of the singlet fermion to realize a TeV baryogenesis without fine tuning the resonant effect. By the exchange of one singlet fermion and two isosinglet diquarks and of one isosinglet diquark and two isotriplet diquarks, a neutron-antineutron oscillation is allowed to verify in the future experiments.

PACS numbers: 98.80.Cq, 11.30.Fs

Within the context of the $SU(3)_c \times SU(2)_L \times U(1)_Y$ standard model (SM), there is a $SU(2)_L$ global anomaly [1] violating the baryon (B) and lepton (L) numbers by an equal amount. This anomalous process becomes fast in the presence of an instanton-like solution, the sphalerons [2], during the period $100 \text{ GeV} \lesssim T \lesssim 10^{12} \text{ GeV}$. The $B + L$ violating but $B - L$ conserving sphaleron processes will not affect any primordial $B - L$ asymmetry and will partially convert the $B - L$ asymmetry to a baryon asymmetry and a lepton asymmetry. So, for a baryogenesis theory above the weak scale, it should firstly generate a $B - L$ asymmetry which is composed of a pure baryon asymmetry [3–6] or a pure lepton asymmetry [7] or any unequal baryon and lepton asymmetries [6]. For example, the $B - L$ asymmetry in the leptogenesis [7] scenario is a lepton asymmetry.

In this paper, we propose a new baryogenesis model to generate the baryon asymmetry at the TeV scale. We extend the SM by four TeV-scale fields (a singlet fermion, an isotriplet and two isosinglet diquark scalars). In our model, the baryon number is softly broken by two units due to the Majorana mass of the singlet fermion as well as the trilinear couplings between one isosinglet diquark and two isotriplet diquarks. The isotriplet diquark has the Yukawa couplings with two left-handed quarks while the isosinglet diquarks have the Yukawa couplings with two right-handed down-type quarks. As for the singlet fermion, it has the Yukawa couplings with one right-handed up-type quark and one isosinglet diquark. The baryogenesis thus can be realized through the three-body decays of the singlet fermion which is lighter than the isosinglet diquarks. In this scenario, we need not fine tune the resonant effect [8], like some leptogenesis models

[9]. Since we have not observed proton decay so far, there is now renewed interest to look for neutron-antineutron oscillation with the advent of ultracold neutrons and storage systems. In the presence of the baryon number violation of two units, our model can avoid the dangerous proton decay, but result in a neutron-antineutron oscillation through the exchange of one singlet fermion and two isosinglet diquarks and of one isosinglet diquark and two isotriplet diquarks. For the parameter choice of the baryogenesis, the induced neutron-antineutron oscillation can be sensitive to the forthcoming experiments.

For simplicity, we do not show the full Lagrangian. Instead, we only write down the terms relevant to our illustration,

$$\begin{aligned} \mathcal{L} \supset & -y_{ai}\delta_a\bar{u}_{Ri}X_R^c - f_{aij}\delta_a\bar{d}_{Ri}^c d_{Rj} - h_{ij}\bar{q}_{Li}^c i\tau_2 \Omega q_{Lj} \\ & -\mu_a\delta_a\text{Tr}(\Omega\Omega) - \frac{1}{2}M_X\bar{X}_R^c X_R + \text{H.c.} - M_{\delta_a}^2\delta_a^*\delta_a \\ & -M_{\Omega}^2\text{Tr}(\Omega^\dagger\Omega). \end{aligned} \quad (1)$$

Here

$$X_R(\mathbf{1}, \mathbf{1}, 0) \quad (2)$$

is the singlet fermion with a baryon number $B = -1$,

$$\delta(\mathbf{3}, \mathbf{1}, \frac{2}{3}), \quad \Omega(\mathbf{3}, \mathbf{3}, -\frac{1}{3}) = \begin{bmatrix} \frac{1}{\sqrt{2}}\omega_{\frac{1}{3}} & \omega_{\frac{2}{3}} \\ \omega_{\frac{4}{3}} & -\frac{1}{\sqrt{2}}\omega_{\frac{1}{3}} \end{bmatrix} \quad (3)$$

stand for the isosinglet and isotriplet diquarks with a baryon number $B = -\frac{2}{3}$, while

$$q_L(\mathbf{3}, \mathbf{2}, \frac{1}{6}) = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad u_R(\mathbf{3}, \mathbf{1}, \frac{2}{3}), \quad d_R(\mathbf{3}, \mathbf{1}, -\frac{1}{3}) \quad (4)$$

denote the SM quarks with a baryon number $B = \frac{1}{3}$. The baryon number is thus softly broken by the Majorana mass of the singlet fermion and by the trilinear

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couplings between the isosinglet and isotriplet diquarks. Note that the Yukawa couplings f and h are symmetric for the quark indices, i.e. $f_{aij} = f_{aji}$ and $h_{ij} = h_{ji}$. We shall work in the bases where the Majorana mass M_X is real so that the Majorana fermion

$$X = X_R + X_R^c = X^c \quad (5)$$

can be well defined.

As the singlet fermion and the isosinglet and isotriplet diquarks are assumed to have the following mass spectrum,

$$2M_\Omega < M_X < M_\delta, \quad (6)$$

the decay of the singlet fermion can only be realized by four three-body modes, i.e.

$$\begin{aligned} X &\rightarrow u_R d_R d_R, \quad X \rightarrow u_R \Omega \Omega, \\ X &\rightarrow u_R^c d_R^c d_R^c, \quad X \rightarrow u_R^c \Omega^* \Omega^*, \end{aligned} \quad (7)$$

where the isosinglet diquarks δ are off-shell. We indicate the three-body decays at tree level and one-loop order in Fig. 1. For our assignment of the baryon numbers, the decays $X \rightarrow u_R d_R d_R$ and $X \rightarrow u_R^c \Omega^* \Omega^*$ break the baryon number by $\Delta B = +1$, while the decays $X \rightarrow u_R^c d_R^c d_R^c$ and $X \rightarrow u_R^c \Omega \Omega$ break the baryon number by $\Delta B = -1$. So, a baryon asymmetry can be expected if the CP is not conserved to induce a difference between the decay widths of the $\Delta B = \pm 1$ processes. We calculate the CP asymmetry at one-loop order¹,

$$\begin{aligned} \varepsilon_X &= \frac{\Gamma_{X \rightarrow u_R d_R d_R} + \Gamma_{X \rightarrow u_R^c \Omega^* \Omega^*} - \Gamma_{X \rightarrow u_R^c d_R^c d_R^c} - \Gamma_{X \rightarrow u_R \Omega \Omega}}{\Gamma_{X \rightarrow u_R d_R d_R} + \Gamma_{X \rightarrow u_R^c \Omega^* \Omega^*} + \Gamma_{X \rightarrow u_R^c d_R^c d_R^c} + \Gamma_{X \rightarrow u_R \Omega \Omega}} \\ &= \frac{3}{2\pi} \frac{\text{Im} \left(\sum_{abck} y_{ak}^* y_{ck} f_{aij} f_{bij}^* \frac{\mu_b \mu_c^* M_X^4}{M_{\delta_a}^2 M_{\delta_b}^2 M_{\delta_c}^2} \right)}{\sum_{abk} y_{ak} y_{bk}^* \left(\sum_{ij} f_{aij}^* f_{bij} + 12 \frac{\mu_a^* \mu_b}{M_X^2} \right) \frac{M_X^4}{M_{\delta_a}^2 M_{\delta_b}^2}}. \end{aligned} \quad (8)$$

Actually, one can find

$$\begin{aligned} &\Gamma_{X \rightarrow u_R d_R d_R} + \Gamma_{X \rightarrow u_R^c \Omega^* \Omega^*} \\ &= \Gamma_{X \rightarrow u_R^c d_R^c d_R^c} + \Gamma_{X \rightarrow u_R \Omega \Omega}, \end{aligned} \quad (9)$$

which is guaranteed by CPT conservation and unitary. We also give the total decay width,

$$\begin{aligned} \Gamma_X &= \Gamma_{X \rightarrow u_R d_R d_R} + \Gamma_{X \rightarrow u_R^c d_R^c d_R^c} + \Gamma_{X \rightarrow u_R \Omega \Omega} \\ &\quad + \Gamma_{X \rightarrow u_R^c \Omega^* \Omega^*} \\ &= \frac{1}{2^9 \pi^3} \sum_{abk} y_{ak} y_{bk}^* \left(\sum_{ij} f_{aij}^* f_{bij} + 12 \frac{\mu_a^* \mu_b}{M_X^2} \right) \\ &\quad \times \frac{M_X^5}{M_{\delta_a}^2 M_{\delta_b}^2}. \end{aligned} \quad (10)$$

For the following demonstration, we would like to introduce the parametrization as below,

$$\begin{aligned} y_{ak} &= \bar{y}_{ak} e^{i\alpha_{ak}}, \quad \alpha_k = \alpha_{1k} - \alpha_{2k}, \\ f_{aij} &= \bar{f}_{aij} e^{i\beta_{aij}}, \quad \beta_{ij} = \beta_{1ij} - \beta_{2ij}, \\ \frac{\mu_a}{M_{\delta_a}} &= \kappa_a = \bar{\kappa}_a e^{i\gamma_a}, \quad \gamma = \gamma_1 - \gamma_2, \\ \frac{M_X}{M_{\delta_a}} &= r_a, \end{aligned} \quad (11)$$

to specify the CP asymmetry and the decay width by

$$\varepsilon_X = \frac{3}{2\pi} \frac{B}{A}, \quad \Gamma_X = \frac{1}{2^9 \pi^3} A M_X \quad (12)$$

with

$$\begin{aligned} A &= \sum_k \bar{y}_{1k}^2 \left(\sum_{ij} \bar{f}_{1ij}^2 + 12 r_1^2 \bar{\kappa}_1^2 \right) r_1^4 \\ &\quad + \sum_k \bar{y}_{2k}^2 \left(\sum_{ij} \bar{f}_{2ij}^2 + 12 r_2^2 \bar{\kappa}_2^2 \right) r_2^4 \\ &\quad + 2 \sum_k \bar{y}_{1k} \bar{y}_{2k} \left[\sum_{ij} \bar{f}_{1ij} \bar{f}_{2ij} \cos(\alpha_k - \beta_{ij}) \right. \\ &\quad \left. + 12 r_1 r_2 \bar{\kappa}_1 \bar{\kappa}_2 \cos(\alpha_k - \gamma) \right] r_1^2 r_2^2, \end{aligned} \quad (13)$$

$$\begin{aligned} B &= \sum_{ijk} [(r_1^2 \bar{y}_{1k}^2 - r_2^2 \bar{y}_{2k}^2) \bar{f}_{1ij} \bar{f}_{2ij} \sin(\beta_{ij} - \gamma) \\ &\quad + (r_2^2 \bar{f}_{2ij}^2 - r_1^2 \bar{f}_{1ij}^2) \bar{y}_{1k} \bar{y}_{2k} \sin(\alpha_k - \gamma)] \\ &\quad \times r_1 r_2 \bar{\kappa}_1 \bar{\kappa}_2. \end{aligned} \quad (14)$$

When the Majorana fermions X go out of equilibrium, their CP violating decays can generate a baryon asymmetry. For example, we consider the weak washout region, where the out-of-equilibrium condition can be described by the following quantity,

$$K = \frac{\Gamma_X}{H} \Big|_{T=M_X} \lesssim 1. \quad (15)$$

Here the Hubble constant H is given by

$$H = \left(\frac{8\pi^3 g_*}{90} \right)^{\frac{1}{2}} \frac{T^2}{M_{\text{Pl}}}, \quad (16)$$

¹ In the case with two or more singlet fermions, we can consider the two-body decays to generate a CP asymmetry. Like the right-handed neutrinos in the seesaw [10] models, the singlet fermions should have a tiny mass split to resonantly enhance the CP asymmetry if they are at the TeV scale. Alternatively, the two isosinglet diquarks can realize the leptogenesis through their two-body decays even if the singlet fermion is absent, similar with the isotriplet Higgs scalars [11, 12]. Again, it is necessary for the low scale isosinglet diquarks to have a fine tuning quasi-degenerate mass spectrum.

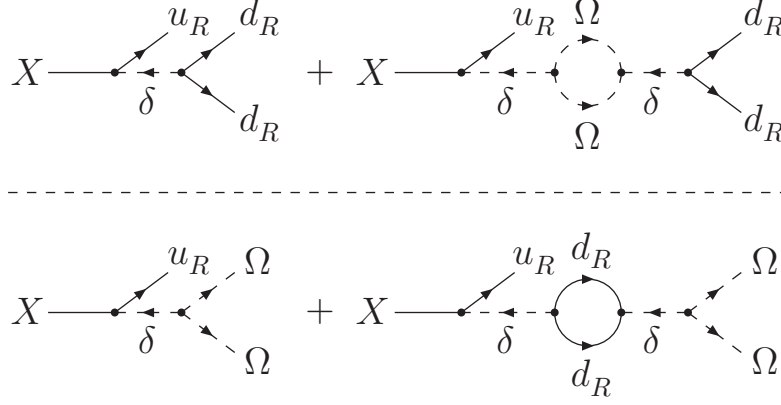


FIG. 1: The three-body decays of the singlet fermion at tree level and one-loop order. The CP conjugation is not shown for simplicity.

with $M_{\text{Pl}} = \mathcal{O}(10^{19} \text{ GeV})$ being the Planck mass and $g_* = \mathcal{O}(100)$ being the relativistic degrees of freedom. The induced baryon asymmetry can approximate to [13]

$$\frac{n_B}{s} \sim \frac{\varepsilon_X}{g_*} \quad \text{for } K \lesssim 1. \quad (17)$$

If the baryogenesis scenario works before the electroweak phase transition, after which the $B - L$ conserving and $B + L$ violating sphaleron processes will be highly suppressed, we should require that other $B - L$ violating interactions (such as the lepton number violation in the seesaw models²) have already decoupled. In the presence of the sphalerons, the induced baryon asymmetry (17), which is equivalent to a $B - L$ asymmetry now, will be partially converted to the final baryon asymmetry,

$$\eta_B = \frac{28}{79} \frac{n_B}{s}. \quad (18)$$

In the other case that the baryogenesis works after the sphaleron epoch, the final baryon asymmetry should be just the induced baryon asymmetry, i.e.

$$\eta_B = \frac{n_B}{s}. \quad (19)$$

² We should forbid or suppress the mixing of the singlet fermion to the right-handed neutrinos in the seesaw model. Otherwise, with the effective Yukawa couplings of the singlet fermion to the SM lepton and Higgs doublets, there will be a proton decay. For this purpose, we can introduce certain discrete symmetries. For example, we can impose a Z_2 symmetry under which the right-handed neutrinos and the SM leptons are odd while the singlet fermion and diquarks as well as the SM quarks and Higgs are even. Furthermore, the singlet fermion can carry a lepton number $L = 1$, rather than the present assignment $B = -1$. In this case, the baryon number violation is changed to be a $B - L$ violation. The baryon number violation in our model and the lepton number violation in the seesaw models can be both induced by a $B - L$ symmetry breaking. If there is a $U(1)_{B-L}$ gauge symmetry, the singlet fermion should be one of the three right-handed neutrinos.

At low energy, the singlet fermion and the diquarks can mediate the baryon number violating interactions as shown in Fig. 2. The effective operators should be

$$\begin{aligned} \mathcal{L}_{eff}^{\Delta B=2} = & - \sum_{ab} \frac{f_{aij}^* y_{ak} y_{bl} f_{bmn}^*}{M_X M_{\delta_a}^2 M_{\delta_b}^2} \bar{d}_{Ri} d_{Rj}^c \bar{u}_{Rk} u_{Rl}^c \bar{d}_{Rn} d_{Rm}^c \\ & - \sum_a \frac{4\mu_a f_{aij}^* h_{kl}^* h_{mn}^*}{M_{\delta_a}^2 M_{\Omega}^4} \bar{d}_{Ri} d_{Rj}^c (\bar{u}_{Lk} d_{Ll}^c \bar{u}_{Lm} d_{Ln}^c \\ & - \frac{1}{2} \bar{u}_{Lk} u_{Ll}^c \bar{d}_{Lm} d_{Ln}^c) + \text{H.c.}, \end{aligned} \quad (20)$$

where the first term is mediated by one singlet fermion and two isosinglet diquarks while the second term is mediated by one isosinglet diquark and two isotriplet diquarks. From the above $\Delta B = \pm 2$ interactions, we can easily read the operators for the neutron-antineutron oscillation,

$$\begin{aligned} \mathcal{L}_{eff}^{n-\bar{n}} = & - \sum_{ab} \frac{f_{a11}^* y_{a1} y_{b1} f_{b11}^*}{M_X M_{\delta_a}^2 M_{\delta_b}^2} \bar{d}_R d_R^c \bar{u}_R u_R^c \bar{d}_R d_R^c \\ & - \sum_a \frac{6\mu_a f_{a11}^* h_{11}^* h_{11}^*}{M_{\delta_a}^2 M_{\Omega}^4} \bar{d}_R d_R^c \bar{u}_L d_L^c \bar{u}_L d_L^c \\ & + \text{H.c.} \end{aligned} \quad (21)$$

We now indicate that our model can simultaneously generate a desired baryon asymmetry and an accessible neutron-antineutron oscillation. For simplicity, we take

$$\begin{aligned} \bar{y}_{1k} = \bar{y}_{2k} = \tilde{y}, \quad \bar{f}_{1ij} = \bar{f}_{2ij} = \tilde{f}, \quad \bar{\kappa}_1 = \bar{\kappa}_2 = \tilde{\kappa}, \\ \gamma - \alpha_k = \beta_{ij} - \gamma = \delta \end{aligned} \quad (22)$$

to derive

$$\varepsilon_X = \frac{9}{\pi} \frac{\tilde{f}^2 \tilde{\kappa}^2 r_1 r_2 (r_1^2 - r_2^2) \sin \delta}{3\tilde{f}^2 (r_1^4 + 2r_1^2 r_2^2 \cos 2\delta + r_2^4) + 4\tilde{\kappa}^2 (r_1^6 + 2r_1^3 r_2^3 \cos \delta + r_2^6)}, \quad (23)$$

as well as

$$\begin{aligned} K = & \frac{3^3 \sqrt{5}}{2^{10} \pi^{\frac{9}{2}} \sqrt{g_*}} \frac{M_{\text{Pl}}}{M_X} \tilde{y}^2 [3\tilde{f}^2 (r_1^4 + 2r_1^2 r_2^2 \cos 2\delta + r_2^4) \\ & + 4\tilde{\kappa}^2 (r_1^6 + 2r_1^3 r_2^3 \cos \delta + r_2^6)]. \end{aligned} \quad (24)$$

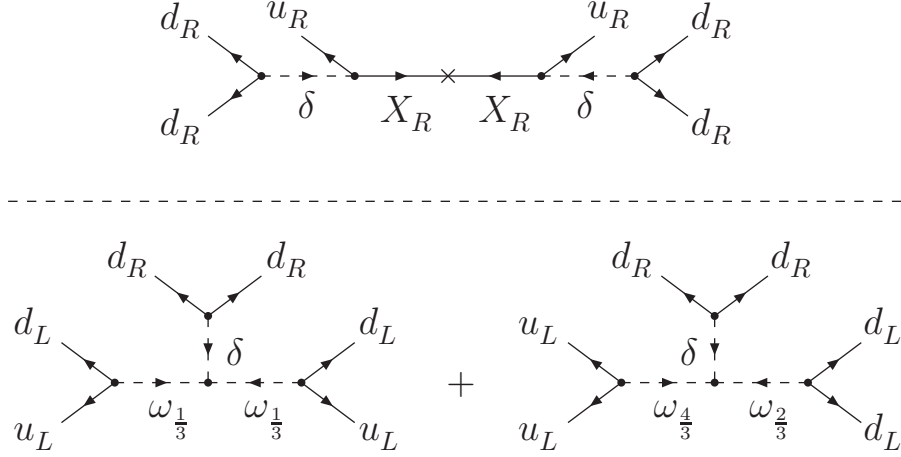


FIG. 2: The baryon number violation at low energy. The CP conjugation is not shown for simplicity.

The singlet fermion and the diquarks are taken at the TeV scale such as

$$M_\Omega = 0.3 \text{ TeV}, \quad M_X = 1 \text{ TeV}, \quad (25)$$

$$M_{\delta_1} = 3 \text{ TeV}, \quad M_{\delta_2} = 3.3 \text{ TeV}.$$

With the leading

$$r_1 \simeq 0.33, \quad r_2 \simeq 0.3, \quad (26)$$

we can obtain

$$\varepsilon_X \simeq 2.9 \times 10^{-8}, \quad K \simeq 0.18, \quad (27)$$

by further inputting

$$\tilde{y} = \tilde{f} = \tilde{\kappa} = 1.5 \times 10^{-3}, \quad \sin \delta = 0.5. \quad (28)$$

The final baryon asymmetry determined by Eq. (18) can explain the measured value,

$$\eta_B \sim 10^{-10}. \quad (29)$$

At the same time, the neutron-antineutron oscillation described by the first term of Eq. (21) can be observed in

the future since its strength is of the order of

$$G_{n-\bar{n}}^{u_R d_R d_R} \sim 10^{-28} \text{ GeV}^{-5}, \quad (30)$$

which is close to the currently experimental bound [14]. As for the neutrino-antineutrino oscillation from the second term of Eq. (21), its strength can also arrive at the same magnitude, i.e.

$$G_{n-\bar{n}}^{u_L d_L d_R} \sim 10^{-28} \text{ GeV}^{-5} \quad \text{for} \quad h_{11} \sim 10^{-5}. \quad (31)$$

In this paper, we extended the SM by a singlet fermion, an isotriplet diquarks and two isosinglet diquarks to generate the cosmological baryon asymmetry with a testable neutron-antineutron oscillation. The new fields are all at the TeV scale. So, they can be verified at colliders (such as the LHC) because the diquarks can be produced through their gauge interactions and then can decay into the quarks and the singlet fermion.

Acknowledgement: PHG is supported by the Alexander von Humboldt Foundation. US thanks R. Cowsik for arranging his visit as the Clark Way Harrison visiting professor.

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